Static and dynamic coupling transitions of vortex lattices in disordered anisotropic superconductors

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We use three-dimensional molecular dynamics simulations of magnetically interacting pancake vortices to study vortex matter in disordered, highly anisotropic materials such as BSCCO. We observe a sharp 3D-2D transition from vortex lines to decoupled pancakes as a function of relative interlayer coupling strength, with an accompanying large increase in the critical current remniscent of a second peak effect. We find that decoupled pancakes, when driven, simultaneously recouple and order into a crystalline-like state at high drives. We construct a dynamic phase diagram and show that the dynamic recoupling transition is associated with a double peak in dV/dI.

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In highly anisotropic superconductors such as BSCCO, the vortex lattice is composed of individual pancake vortices [1]. These pancakes, which interact both magnetically and through Josephson coupling, align under certain conditions into elastic lines resembling those found in isotropic superconductors. Three-dimensional (3D) line-like behavior has been observed in transformer geometry measurements [2], muon-spin-rotation [3] and neutron scattering [4]. Under different conditions, however, the pancake vortices in each layer move independently of the other layers, and the system acts like a stack of independent thin film superconductors. Such two-dimensional (2D) behavior has also been seen in transformer experiments [5]. Thus in layered superconductors two different effective dimensionalities of the vortex pancake lattice may appear, each with different characteristic properties.

Layered superconductors exhibit a striking second peak in magnetization measurements [4,6–10], corresponding to an abrupt increase in the critical current of the material as the applied field is increased. This second peak is especially sharp in BSCCO, as shown in local Hall probe measurements [7,9,10] and recent Josephson plasma frequency measurements [11]. The lattice appears ordered at fields below the transition and disordered above. There seems to be no widely accepted agreement on the mechanism behind this transition, although numerous scenarios have been suggested, including vortex entanglement [13], dislocation proliferations [12], dynamic effects [14], or a 3D to 2D transition in the vortex pancake lattice [4,7,15,16,18]. The effect of strong disorder on a possible 3D-2D transition is unclear, and also it is not known how the transport properties would be affected by a 3D-2D transition.

In 2D systems with uncorrelated pinning, the vortex lattice can be dynamically reordered by an applied driving current, passing from a glassy state at zero drive, through plastic flow [19], to a reordered state at high current [20–23]. In layered systems, when the between plane interactions of pancakes is weak enough that the pancakes are decoupled, the pancakes on each plane should reorder when a high enough driving current is applied. This reordering may also be accompanied by a dynamically driven recoupling transition [20], but it is unclear where this transition could be located in relation to the 2D reordering transition, and how it is affected by the externally applied magnetic field.

To address the issue of possible 3D-2D transitions in disordered anisotropic materials, we have developed a simulation which allows for decoupling by incorporating the correct magnetic interactions between vortex pancakes. We show that a sharp 3D-2D transition occurs when the relative strength of interlayer and intralayer pancake interactions is varied, and that this transition is associated with a *sharp increase* in the critical current. Furthermore, the system exhibits a rich array of dynamic 3D phases when driven by a current [20]. We show that 2D decoupled pancakes can be dynamically recoupled in a transition that occurs *simultaneously* with the dynamic ordering in each plane. We construct a phase diagram as a function of interlayer coupling and applied driving force, and show that a sharp, experimentally observable second peak in dV/dI is associated with the dynamic recoupling transition.

The magnetic interactions between pancakes in a layered material have the same logarithmic form present in thin films, but are highly anisotropic [1,16,24]. We have performed simulations in which pancakes in all layers interact magnetically with long range interactions [25,26], in contrast to other simulations, which treated only nearest layer interactions [27,28]. Our approach compliments calculations based on Lawrence-Doniach models [29]. The pancake interactions are long range both in and between planes, and are treated according to Ref. [30]. Josephson coupling is neglected as a reasonable approximation for materials in which the anisotropy γ is sufficiently large [16].

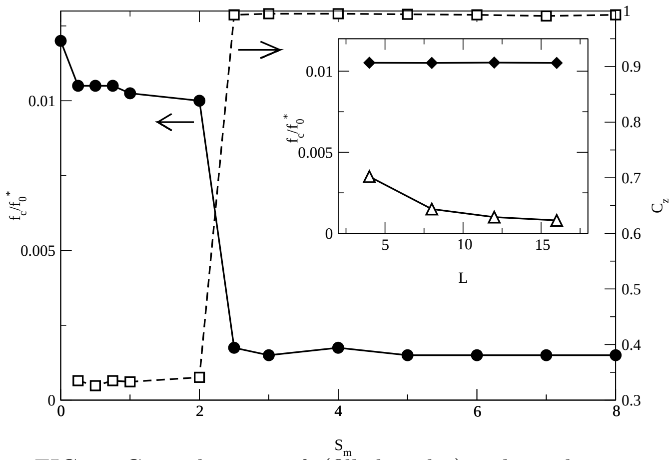

FIG. 1. Critical current f_c (filled circles) and interlayer correlation C_z (open squares) versus interlayer coupling strength s_m. A transition from 2D to 3D behavior occurs between $s_m = 2$ and $s_m = 2.5$. Inset: Critical current f_c for samples with $L = 4$, 8, 12, and 16 layers. Filled diamonds: f_c for $s_m = 0.5$, in the 2D regime. Open triangles: f_c for $s_m = 5.0$, in the 3D regime.

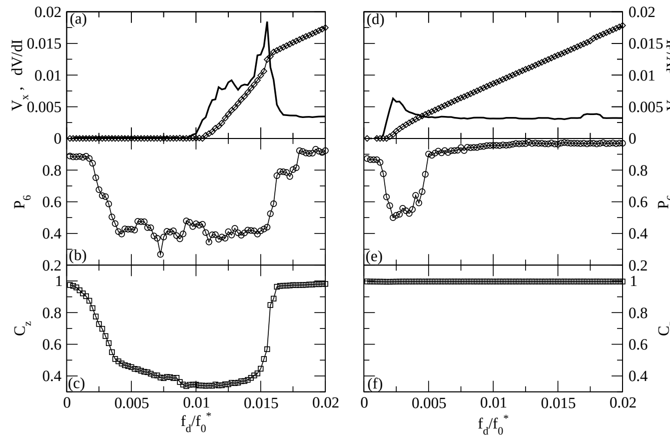

FIG. 2. (a) Diamonds: $V_x = (1/N_v)\sum_1^{N_v} v_x$; heavy line: dV/dI, for a sample with $s_m = 1.5$ that undergoes dynamic recoupling. (b) P_6, the fraction of sixfold coordinated vortices, for $s_m = 1.5$. (c) C_z, the interlayer correlation, for $s_m = 1.5$. (d) Diamonds: V_x; heavy line: dV/dI, for a sample with $s_m = 4.0$, which remains coupled at all drives. (e) P_6, the fraction of sixfold coordinated vortices, for $s_m = 4.0$. (f) C_z, the interlayer correlation, for $s_m = 4.0$.

The overdamped equation of motion, at $T = 0$, for vortex i is given by $\mathbf{f}_i = -\sum_{j=1}^{N_v} \nabla_i \mathbf{U}(\rho_{i,j}, z_{i,j}) + \mathbf{f}_i^{vp} + \mathbf{f}_d = \mathbf{v}_i$, where N_v is the number of vortices, and $\rho_{i,j}$ and $z_{i,j}$ are the distance between pancakes i and j in cylindrical coordinates. The system has periodic boundaries in-plane and open boundaries in the z direction. The magnetic energy between pancakes is [17]

$$\mathbf{U}(\rho_{i,j}, 0) = 2d\epsilon_0 \left((1 - \frac{d}{2\lambda}) \ln \frac{R}{\rho} + \frac{d}{2\lambda} E_1 \right)$$

$$\mathbf{U}(\rho_{i,j}, z) = -s_m \frac{d^2\epsilon_0}{\lambda} \left(\exp(-z/\lambda) \ln \frac{R}{\rho} - E_2 \right)$$

where $E_1 = \int_\rho^\infty d\rho' \exp(\rho'/\lambda)/\rho'$, $E_2 = \int_\rho^\infty d\rho' \exp(R/\lambda)/\rho'$, $R = 22.6\lambda$, the maximum radial distance, $\epsilon_0 = \Phi_0^2/(4\pi\lambda)^2$, λ is the London penetration depth, $d = 0.005\lambda$ is the interlayer spacing, and ξ is the coherence length. We vary the relative strength of the interlayer coupling using the prefactor s_m. The uncorrelated pins are modeled by parabolic traps that are randomly distributed in each layer. The vortex-pin interaction is given by $\mathbf{f}_i^{vp} = \sum_{k=1}^{N_{p,L}} (f_p/\xi_p)(\mathbf{r}_i - \mathbf{r}_k^{(p)})\Theta((\xi_p - |\mathbf{r}_i - \mathbf{r}_k^{(p)}|)/\lambda)$, where the pin radius $\xi_p = 0.2\lambda$, the pinning force $f_p = 0.02 f_0^*$, and $f_0^* = \epsilon_0/\lambda$. The case of stronger pins is considered in [25]. The driving current must be increased slowly enough for the system to equilibrate at each drive [31]. Here f_d is increased by $0.00025 f_0^*$ every 35000 time steps. We have simulated a $16\lambda \times 16\lambda$ system with a vortex density of $n_v = 0.35/\lambda^2$ and a pin density of $n_p = 1.0/\lambda^2$ in each of $L = 8$ layers. This corresponds to $N_v = 89$ vortices and $N_p = 256$ pins per layer, with a total of 712 pancake vortices. We have checked for finite size effects on systems containing up to 42 layers and 3738 pancakes.

In the equilibrium state of the vortex lattice at zero drive, we find a *sharp 3D-2D transition* from vortex pancakes to vortex lines when the strength s_m of the interlayer coupling is decreased, as shown in Fig. 1. We quantify the transition by measuring the spatial correlation of pancakes in neighboring planes, $C_z = 1 - \langle (|(\mathbf{r}_{i,L} - \mathbf{r}_{i,L+1})|/(a_0/2))\Theta(a_0/2 - |(\mathbf{r}_{i,L} - \mathbf{r}_{i,L+1})|)\rangle$, where a_0 is the vortex lattice constant. A clear sharp drop in C_z with decreasing s_m appears in Fig. 1 at $s_m = 2.0$ for a sample with $L = 8$ layers. The 3D-2D transition is accompanied by a large *increase* in the critical current f_c, as seen in Fig. 1. For weak interlayer coupling, $s_m \le 2.0$, the different layers of the sample depin independently and f_c is close to the value it would have in a 2D sample. Here, f_c is insensitive to the number of layers in the system, as can be seen by comparing the data from samples with L =4 to 16 in the inset of Fig. 1. In contrast, coupled lines of pancakes at $s_m > 2.0$ average the random pinning over their length and become much less effectively pinned. Therefore f_c decreases with increasing number of layers as seen in the inset of Fig. 1.

When the magnetic field H increases, pancakes within a plane are brought closer together, but the distance between planes is unchanged. Thus increasing H corresponds to weakening the coupling between planes by decreasing s_m. Therefore, our results support the suggestion that the sharp second peak observed in magnetization measurements results from a dimensional change in the vortex lattice from weakly pinned 3D vortex lines to strongly pinned 2D pancakes as the magnetic field is

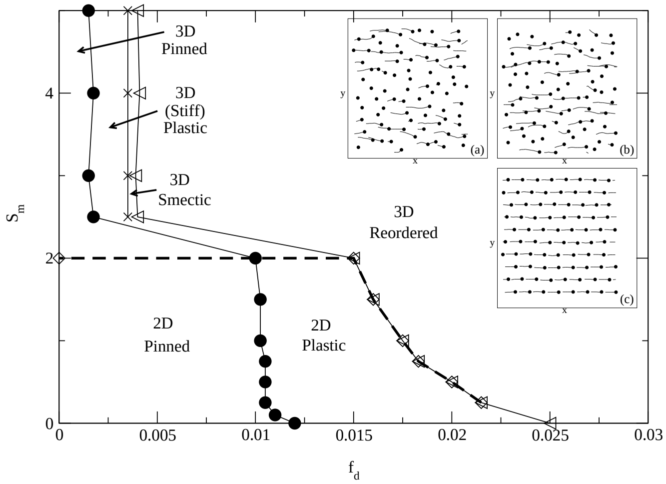

FIG. 3. Phase diagram for varying interlayer coupling s_m and driving force f_d. Filled circles: depinning line. X's: smectic transition line (in 3D phase only). Triangles: in-plane reordering line. Diamonds and heavy dashed line: recoupling line. For samples with $s_m \leq 2.0$, a dynamic transition into the 3D reordered state occurs at high drives. Inset: Vortices (filled circles) and vortex trajectories (lines) at two different currents. (a) and (b): Vortex trajectories in top and bottom layers, respectively, for a system with $s_m = 1.5$ at $f_d/f_0^* = 0.0125$, in the 2D plastic flow regime. The vortex positions and flow are different in each layer. (c): Vortex trajectories for a system with $s_m = 1.5$ at $f_d/f_0^* = 0.02$, in the 3D reordered flow regime.

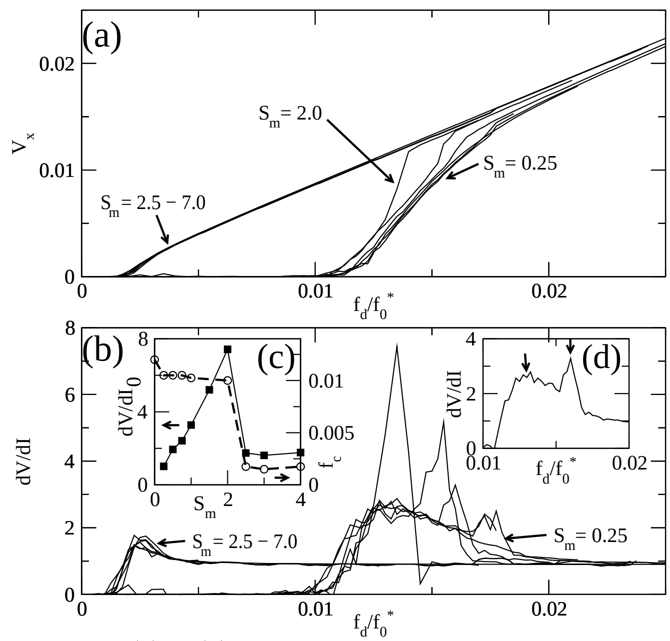

FIG. 4. (a) $V_x(I)$ curves for samples with different values of s_m. From right to left, s_m =0.25, 0.5, 0.75, 1.0, 1.5, 2.0, 2.5, 3.0, 4.0, 5.0, 6.0, and 7.0. Samples with $s_m > 2.0$ are coupled at all drives; samples with $s_m \leq 2.0$ undergo dynamic recoupling. (b) dV/dI curves for the same samples, from right to left, as listed above. Samples with $s_m > 2.0$ show a single peak in dV/dI associated with the plastic flow regime at currents just above the 3D depinning current of $f_d/f_0^* = 0.0015$. Samples with $s_m \leq 2.0$ show *two* peaks in dV/dI. (c) Filled squares: The value of dV/dI_0, the maximum in the dV/dI curve, for samples with different s_m. dV/dI_0 increases significantly as the transition value of s_m is approached from below. Open circles and dashed line: f_c versus s_m. (d) dV/dI for a single sample with $s_m = 1.0$ illustrating the double peak feature. The first broad peak (left arrow) appears just above the 2D depinning current of $f_d/f_0^* = 0.010$ and is associated with 2D decoupled plastic flow. The second sharp peak (right arrow) is associated with the dynamic recoupling transition.

increased [32]. The behavior in f_c that we observe indicates that *a sharp change in transport properties can occur in a disordered system as a result of a change in the effective dimensionality.* Furthermore, the sharpness of the transition found both here and in experiments suggests that the 3D-2D transition is *first order.*

We next consider the question of a possible dynamic recoupling transition by applying a driving force. When the vortex lattice begins to move for $f_d > f_c$, it undergoes plastic tearing due to the strong pinning in our sample. For decoupled samples with $s_m \leq 2.0$ each plane performs *independent 2D plastic flow*, as seen by the different vortex positions and trajectories in the top and bottom layer of the sample shown in Fig. 3(a,b). When high drives are applied, however, the pancakes *recouple* into lines and all planes begin to move in unison [Fig. 3(c)].

The reordering transition is shown in more detail in Fig. 2(a-c). Here, for a sample with $s_m = 1.5$, the recoupling transition in C_z [Fig. 2(c)] is sharp and occurs *simultaneously* with the in-plane reordering transition indicated by P_6 [Fig. 2(b)]. Furthermore, a sharp peak in dV/dI appears at the transition, which will be discussed in more detail below. In contrast, as seen in Fig. 2(d-f), a sample with $s_m = 4.0$ that is above the static 2D-3D transition contains vortices that move as stiff 3D lines, and shows the same reordering transitions seen in previous work on effectively two-dimensional systems [22].

We summarize the behavior of the system in the phase diagram of Fig. 3. The coupled vortices with $s_m > 2.0$ undergo plastic flow of stiff lines, pass through a smectic state, and finally reorder into a crystalline-like state at high drives. The plastic flow and smectic regions shrink as the number of layers is increased, and finally disappear, so that for $L = 16$ and $s_m = 5$ we observe elastic depinning directly into the 3D ordered state, with no plastic flow. Decoupled vortices with $s_m \leq 2.0$ depin into a 2D plastic flow phase in which each layer moves independently. The vortices switch abruptly from 2D to 3D behavior at the recoupling transition line, so they directly enter the 3D ordered state. The dynamic recoupling transition line and in-plane reordering transition line fall on top of each other in the phase diagram.

As shown in Fig. 4(b), the dynamic recoupling and simultaneous reordering are associated with a sharp *peak* in the dV/dI curve. This peak is *distinct* from the broader peak in dV/dI associated with plastic flow of the vortex

lattice, as indicated in Fig. 4(d). The sharp peak disappears into the background value of dV/dI and is not observed when the interlayer coupling becomes too weak. The height of the reordering peak increases rapidly as the static 2D-3D transition value of s_m is approached from below, as indicated in Fig. 4(c), and simultaneously the current at which the reordering peak appears shifts downwards towards the location of the broad plastic peak. To understand the reordering peak, note that the 2D decoupled lattice depins at the high f_c associated with the 2D limit. When the lattice recouples, it must cross from the low V_x response in the 2D plastic limit up to the higher 3D elastic V_x response curve at the recoupling transition. The location of the depinning transition is not affected by the value of s_m since it is purely a 2D effect; however, the recoupling transition is shifted to lower driving currents as s_m increases. As a result, the rising V(I) curve becomes steeper as the static transition point is approached from below, as can be seen for s_m =1.0, 1.5, and 2.0 in Fig. 4(a). The maximum value of dV/dI, which we call dV/dI_0, correspondingly increases, as shown in Fig. 4(c). When the static 2D-3D transition is crossed at $s_m = 2.0$, the second sharp peak disappears. The behavior of this sharp peak in dV/dI, associated with the dynamic recoupling transition, should be experimentally observable in transport measurements performed at fields approaching the second peak from above, when the vortex pancakes are expected to be decoupled.

In summary, we have used a 3D molecular dynamics simulation employing the magnetic interactions of pancake vortices to study the dynamic phases of vortex matter in disordered highly anisotropic materials such as BSCCO. As a function of the relative interlayer coupling strength, we observe a sharp 3D-2D transition from vortex lines to decoupled pancakes. We find an *abrupt large increase in the critical current* as the 3D-2D line is crossed in a direction corresponding to increasing H, with decoupled pancakes being much more strongly pinned. At driving currents well above depinning, we find that the decoupled pancakes *simultaneously recouple and reorder* into a crystalline-like state at high drives. We construct a phase diagram as a function of interlayer coupling and show that the recoupling transition coincides with the single-layer recrystallization transition. We show that the recrystallization is associated with an experimentally observable double peak in dV/dI and that the peak height grows rapidly as the static recoupling transition point is approached from below.

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